

A broad iron $K\alpha$ line at $z = 1.146$

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ABSTRACT

We report the discovery of a strong iron $K\alpha$ line in the hard X-ray selected source CXOJ 123716.7+621733 in the *Chandra* Deep Field North survey at $z = 1.146$. The analysis is made possible by the very deep exposure ~ 2 Ms and low background of the ACIS detector. The line profile seems to be inconsistent with a narrow feature. The best fit solution is achieved with a broad line. Most of the flux in the broad component originates at energies below 6.4 keV with a shape similar to that expected from emission in the innermost regions of the accretion disk.

Key words: Galaxies: active – Galaxies: individual: CXOJ 123716.7+621733 – X-rays: galaxies

1 INTRODUCTION

The strongest emission feature in the hard X-ray spectrum of an active galactic nucleus (AGN) is the fluorescent Fe $K\alpha$ emission line at 6.4–7 keV. Since its discovery by early X-ray observations, it is by now recognized to be an ubiquitous feature in the high energy spectra of Seyfert galaxies. The line properties – in particular the centroid energy, intensity and profile – carry important diagnostic information about the dynamics and physics of the region where the emission originates. For example, the best fit line energy is a measure of the ionization status of the gas, the line equivalent width (EW) is strongly correlated with the amount of fluorescing material, while the detection of a broad asymmetric profile, first resolved with ASCA by Tanaka et al. (1995) in the bright Seyfert 1 galaxy MCG–6–30–15, is considered the most direct evidence of the presence of an accretion disc extending down to a few gravitational radii of the central black hole. The power of X-ray spectroscopy as a diagnostic of the AGN physics is witnessed by hundreds of papers (see Fabian et al. 2000; Reynolds & Nowak 2003, for extensive reviews).

The detailed study of the iron line properties requires a large collecting area and good energy resolution. For this reason, most of the results obtained so far are limited to nearby, low luminosity Seyfert galaxies (e.g. Turner et al. 2002; Fabian et al. 2002; Dewangan, Griffiths & Schurch 2003). X-ray observations of sizable samples of higher luminosity AGN, extending in the quasars regime ($L_X > 10^{44}$ erg s^{−1}), reveal the evidence of a trend whereby the strength of the iron line decreases and the centroid moves to higher energies (Iwasawa & Taniguchi 1993, Nandra et al. 1997a,

George et al. 2000, Reeves & Turner 2000, Page et al. 2004). The search for iron line emission at high redshift is hampered by the statistical quality of the X-ray spectra and only a few tentative detections at the 2σ level have been reported. (e.g., Vignali et al. 1999; Reeves et al. 2001; Norman et al. 2002; Gandhi et al. 2004).

Deep, sensitive X-ray observations carried out with both *Chandra* and XMM–*Newton* now offer the opportunity to search for the presence of iron emission line with relatively large well defined samples of X-ray selected sources, down to limiting fluxes which provides the possibility to probe a much larger redshift range. Motivated by this possibility, we have started a systematic search for emission line features among the serendipitous sources in the deepest X-ray observations available to date.

Here we report the detection of a broad iron line in the X-ray source CXOJ 123716.7+621733, serendipitously detected in the 2 Ms exposure of the *Chandra* Deep Field–North (CDF–N; Alexander et al. 2003a). The spectroscopic redshift ($z = 1.146$) is based on a single [OII] $\lambda 3727$ line (Barger et al. 2002). The compact optical morphology, the hard X-ray spectrum and the presence of a radio source coincident with the X-ray position (Richards 2000) leaves no doubt about the AGN nature of this object. On the basis of the available optical spectrum it is not possible to determine if the object is a Type 1 or a Type 2 AGN. Unfortunately, at the expected Mg II $\lambda 2798$ position the optical spectrum is contaminated by strong atmospheric bands and night-sky emission lines. The source is classified as radio-quiet on the basis of the 1.4 GHz flux density (0.346 mJy) and optical magnitude (Barger et al. 2003). A cosmological model with $H_0 = 70$ km s^{−1} Mpc^{−1}, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ is assumed.

2 X-RAY DATA ANALYSIS

The X-ray data retrieved from the public archive have been processed with standard procedures making use of the calibrations associated with the *CIAO* software¹ (version 2.3). Since the 20 separate *ACIS-I* observations that make the 2Ms CDFN have been performed at different roll angles and aim-points, the source position in detector coordinates changes during the whole observation. Since the CCD response depends on the position over the detector, source counts have been extracted from each of the 20 observations taking into account the dependence in size of the PSF with off-axis angle. The position of our target is always between 3 to 5 arcmin from the aim-point, thus the extraction radius was varied from 4 to 5 arcsec enclosing a constant fraction (90%) of the PSF. Background regions were chosen locally for each single observation. The time dependent quantum efficiency degradation² of the *ACIS* at low energies was also taken into account in the computation of ancillary response files for each dataset. Spectra, response matrices and effective areas, weighted by the number of counts in each observation, were summed using standard *FTOOLS* routines. There is no evidence of substantial flux variability. The background subtracted count rates in each of the 20 single observations never deviate from the average (~ 1.4 counts/ksec) by more than 20% with the exception of three exposures where the variation is of the order of 50%. The resulting effective exposure time of 1840 ks and the net source counts (2620 in the 0.6–7 keV band) are fully consistent with the values quoted in the 2Ms X-ray catalog (Alexander et al. 2003a). The slightly non-standard energy range considered for the spectral analysis is driven by the choice to keep the background level always below the 10% of the total counts. The summed spectrum was then rebinned with at least 25 counts per bin. Spectral analysis was carried out with *XSPEC* (Version 11.2), errors are reported at the 90% confidence level for one interesting parameter ($\Delta\chi^2 = 2.71$).

2.1 Spectral analysis

A single power law fit plus absorption (first line of Table 1) provides a good description of the broad band 0.6–7 keV continuum. The power law slope is rather flat ($\Gamma \simeq 1.5$) while the best fit column density ($\sim 1.8 \times 10^{22}$ cm⁻² rest-frame) is clearly inconsistent with the Galactic column density towards the CDF-N ($N_{Hgal} = 1.6 \times 10^{20}$ cm⁻²). The observed 2–10 keV flux of $\sim 1.7 \times 10^{-14}$ erg cm⁻² s⁻¹ corresponds to a rest frame luminosity of $\sim 7.8 \times 10^{43}$ erg s⁻¹ which is typical of a bright Seyfert 1 galaxy. The broad band 0.5–10 keV unabsorbed luminosity is $\sim 1.2 \times 10^{44}$ erg s⁻¹.

Significant residuals around 3 keV are clearly evident (Fig. 1), strongly indicating the presence of a line-like feature.

We therefore added a Gaussian line with rest frame energy fixed at 6.4 keV. Leaving both the line width and redshift free to vary the fit quality is significantly improved (at more than 99.99999% level according to the F-test) and statistically acceptable (second line in Table 1). The line width is broader than the instrument resolution. Moreover,

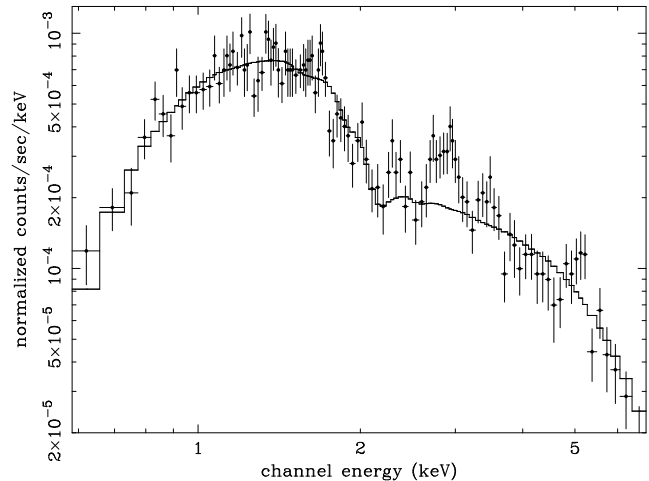


Figure 1. The source spectrum rebinned with at least 25 counts per channel is fitted with a single power law ($\Gamma = 1.48$) plus intrinsic absorption $N_H \simeq 1.8 \times 10^{22}$.

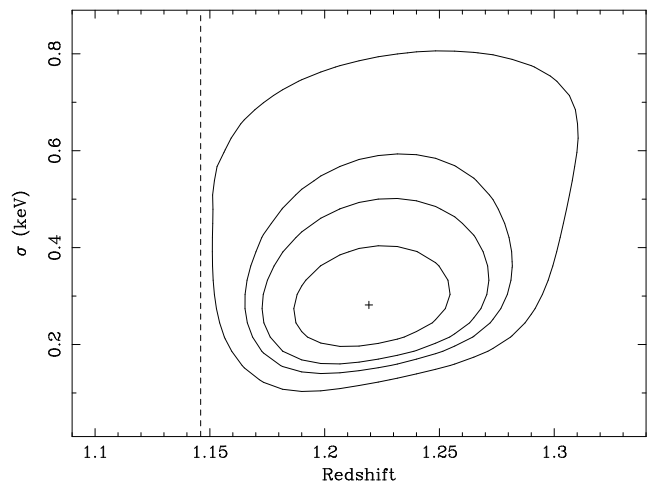


Figure 2. 68%, 90%, 95% and 99% confidence contours for the line redshift and Gaussian width σ . The vertical dashed line corresponds to the spectroscopic redshift.

the best fit energy centroid is significantly higher than that expected on the basis of the spectroscopically measured redshift (see Fig. 2). The discrepancy would be even higher if a ionised line at 6.7 or 6.96 keV is considered.

Given that the redshift obtained from optical spectroscopic observations is unlikely to be affected by such a large error, we have fixed the centroid of the neutral line at $z = 1.146$ and repeated the fitting procedure. Leaving the line width free to vary, the quality of the fit is marginally worse than in the previous case (third line in Table 1). From a visual inspection of the spectrum it appears evident that most of the line width has to be ascribed to a red tail with respect to the redshifted centroid of 6.4 keV. This effect is clearly seen in Figure 3 where the line width is fixed at the instrumental energy resolution.

2.2 Safety checks

Although the statistical significance regarding the presence of a line feature at 2.9 keV is very robust, as indicated by the

¹ <http://cxc.harvard.edu/ciao/>

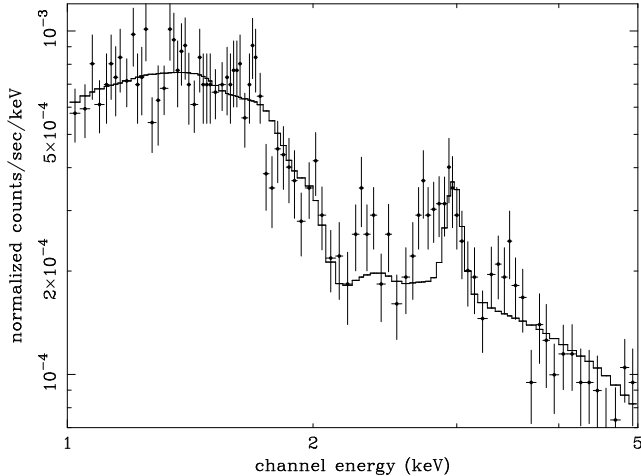
² <http://cxc.harvard.edu/cal/ACIS/Cal-prods/qeDeg/>

Table 1. Spectral fit parameters

Model	Γ	N_H^a	z_{line}	σ (keV)	EW (eV)	$\chi^2/d.o.f.$
Absorbed power law	1.48 ± 0.07	1.8 ± 0.3	134.6/110
Absorbed power law + K α line	1.50 ± 0.08	1.7 ± 0.3	$1.20^{+0.06}_{-0.02}$	$0.28^{+0.15}_{-0.10}$	350^{+109}_{-103}	94.8/107
Absorbed power law + K α line	1.52 ± 0.09	1.7 ± 0.3	1.146(f)	$0.6^{+0.3}_{-0.4}$	434^{+179}_{-193}	104.4/108

^a units of 10^{22} cm^{-2} .

(f) fixed parameter


Figure 3. A zoom of the 1–5 keV spectrum fitted with a narrow 6.4 keV line at the source redshift $z = 1.146$. Spectral binning and continuum spectrum parameters as in Fig. 1.

F-test value, further checks have been performed to assess the overall strength of our results.

First, background spectra have been extracted from several regions with different sizes and shapes. In all the cases the background level is always negligible over most of the considered energy range. In particular, in the 2.5–3 keV band, where the line feature is present, the average background level never exceed 5–6% of the total counts.

Then, to rule out the possibility that something unusual has occurred combining the 20 individual exposures, source spectra have been extracted for three different time intervals in such a way that each summed spectrum contains the same number of counts (about 800–1000). A clear line-like feature is always present around 2.9 keV, though with a lower statistical significance owing to the reduced counting statistic.

Finally, to further assess the statistical quality of our results, extensive Monte Carlo simulation (up to 100,000 trials) have been carried out using the `fakeit` routine within `XSPEC` (see Alexander et al. 2003b for a similar approach). The input model was an absorbed power law spectrum with the best fit parameters determined from the observed data (first row of Table 1). The simulated spectra were then fitted adding a redshifted broad Gaussian line with a centroid energy fixed at 6.4 keV rest-frame. The line intensity, width and redshift are free to vary. For each simulated spectrum the $\Delta\chi^2$ value obtained by adding three more free parameters has been computed. In none of the 100,000 simulations

the $\Delta\chi^2$ value is as large as that obtained from the fit to the real data. More specifically, the largest $\Delta\chi^2$ of the simulation with 100,000 trials is about 18 to be compared with $\Delta\chi^2 \simeq 40$ as obtained from the observed spectrum (Table 1). It is concluded that the probability to detect such a line feature by chance is negligible, in good agreement with the F-test results.

2.3 A relativistic line

The overall properties of the line profile are, at least qualitatively, similar to those of an emission line originating in the innermost region of an accretion disc. We next fitted the data with the Schwarzschild disk line model of Fabian et al. (1989). It is well known that disk models have a considerable parameter degeneracy and thus the interpretation of the results obtained by standard fitting procedures is not straightforward. Given that the quality of our data is not such to allow a detailed parameter investigation, the best fit solutions and associated error bars have to be treated with caution.

In all the fits we have assumed a neutral iron K α line at 6.4 keV rest frame. First of all we have considered a model where only the inner disc radius is fixed at the last stable orbit of a non-rotating black hole ($6R_S$). The quality of the fit is statistically acceptable ($\chi^2/d.o.f.=94/106$) and the improvement with respect to a single power law is significant at more than 99.9999% level according to an F-test. The formal best fit solution returns a power law index for the disk emissivity (which scales as R^{-q}) $q \sim 2.5$ and an inclination angle of 7 degree, while the outer disk radius (R_{out}) is basically unconstrained towards high values. The line equivalent width (EW) in the observed frame is $\sim 425 \pm 125$ eV, corresponding to $\sim 910 \pm 270$ eV in the rest-frame. The 1–5 keV X-ray spectrum deconvolved by the instrument response is reported in Figure 4. Assuming a rather optimistic criterion of $\Delta\chi^2=4.6$ (corresponding to 90% interval for two parameters) we have tried to estimate errors for both R_{out} and q , which, as expected are only poorly constrained: $R_{out} > 35R_S$, $q < 3.5$.

For a disk centrally illuminated by a point X-ray source situated at a height H above the disk center, q is expected to lie in the range 0–3 (Fabian et al. 1989) depending on the considered disc radius. Most of the line flux originates from radii of the order of H where the emissivity index is $q \sim 2$ (Laor 1991). Assuming such a value for the disc emissivity law, it is possible to better constrain the outer disc radius and inclination angle (Fig. 5). As far as the disc inclination angle is concerned, we note that it is always lower than ~ 30

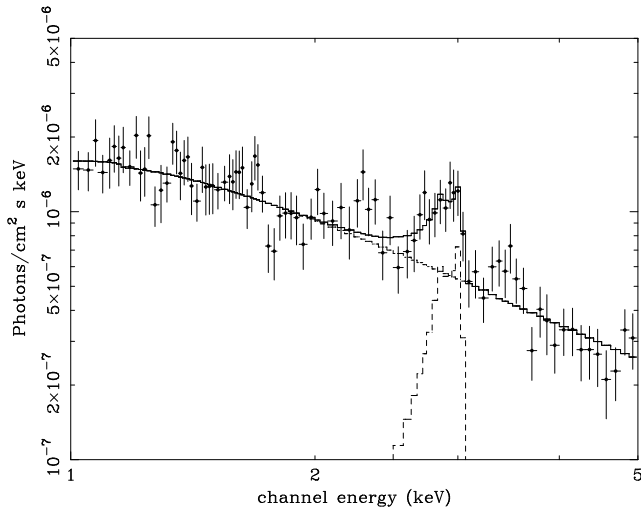


Figure 4. The unfolded spectrum fitted with an absorbed power law ($\Gamma \simeq 1.5$; $N_H \simeq 1.7 \times 10^{22} \text{ cm}^{-2}$) plus a relativistic disk line. Spectral binning as in Fig. 1.

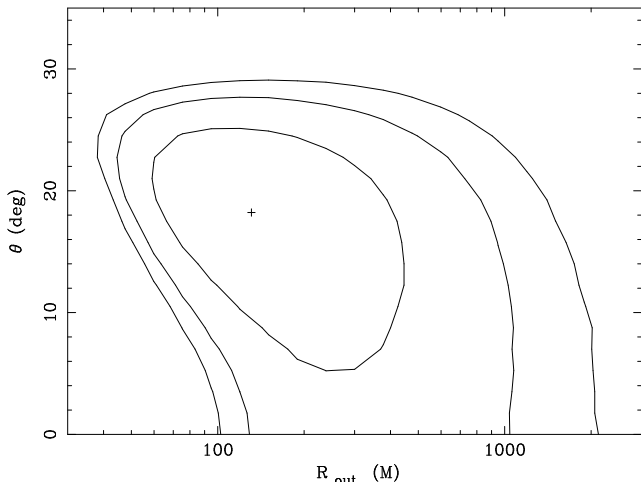


Figure 5. 68%, 90% and 95% confidence contours for the disc inclination angle and outer radius R_{out}

degrees (at a confidence level of 99%) and rather insensitive to the variation of the other disk line parameters. Fixing the outer radius to a value of $400R_S$ the best fit emissivity law and associated 90% errors is $q \simeq 2.3 \pm 0.6$.

The results above described do not substantially change if the continuum spectrum is fitted with a power law plus a reflection component from cold gas. More specifically a good fit ($\chi^2/d.o.f. = 97/107$; significant at more than 99.9999% level) is obtained when the continuum spectrum is parameterized by a power law with $\Gamma = 1.8$ plus reflection from cold gas subtending a 2π sr solid angle at the X-ray source. The observed equivalent width (EW) with respect to the reflected continuum is about 400 ± 120 eV which corresponds to about 860 ± 260 eV in the source rest frame.

3 DISCUSSION AND CONCLUSIONS

A strong emission feature due to the $K\alpha$ iron line has been clearly detected in the X-ray spectrum of the rela-

tively bright, hard X-ray source CX0J 123716.7+621733 at $z=1.146$ in the *Chandra* Deep Field North. The broad band 0.6–7 keV *Chandra* spectrum is best described by a relatively hard ($\Gamma \simeq 1.5$) power law plus significant intrinsic absorption $N_H \sim 1.8 \times 10^{22} \text{ cm}^{-2}$. An almost equally good fit is obtained if the continuum emission is parameterized with a steeper ($\Gamma = 1.8$) slope plus a reflection component as commonly observed in nearby Seyfert galaxies.

The line profile is not consistent with a narrow feature, being significantly broader than the ACIS-I CCD resolution at that energy. Such a result does not depend on the adopted shape of the underlying continuum.

In order to reproduce both the observed width and the optical spectroscopic redshift, most of the line flux has to originate in a red wing. An adequate description of the overall line shape has been obtained with a relativistic line model. Although the quality of the data is not such to break the degeneracy between the various line parameters, the present observation suggests an almost face-on orientation of the accretion disk.

The line equivalent width (860 ± 260 eV) is larger than the average values measured by *ASCA* for a sample of nearby bright Seyfert galaxies. Nandra et al (1997b) report an average value of 230 ± 60 eV, for a relativistic line model. Plausible possibilities include iron overabundance as in MCG-6-30-15 (see e.g. Lee et al. 1999) and/or an enhanced contribution of the reflected flux possibly associated to time variability. The latter possibility appears unlikely given the lack of significant flux variability over more than two years. It must be noted that large values of the EW are not unusual among relatively faint X-ray sources (George et al. 2000) and likely to be due to a selection effect associated to the uncertainties in modelling the continuum and line spectrum.

The broad band properties of CX0J 123716.7+621733 (namely, the high X-ray to optical ratio, ($\log f_X/f_{opt} \simeq 1$), the X-ray column density ($> 10^{22} \text{ cm}^{-2}$) and the optical, near-infrared colors ($B - V = 0.7$, $R - K = 4.4$; Barger et al. 2003)) indicate substantial obscuration of the nuclear source. There is also no evidence of typical AGN emission lines in the low resolution optical spectrum (Barger et al. 2002).

The present results indicate that the iron $K\alpha$ line could be the strongest AGN signature in the broad band spectra (from optical to X-rays) of distant, obscured AGN for which only a low signal-to-noise optical spectrum covering a relatively small range of wavelengths is available, and highlight the uniqueness of X-ray observations in the study of super-massive black holes at cosmologically interesting distances.

The study of relativistically broadened iron line profiles would greatly benefit from deep X-ray observations with the XMM-*Newton* large collecting area telescopes. Observations with the new generation of X-ray observatories (*Constellation X* and *XEUS*) will allow systematic studies of iron line properties at high redshifts.

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